First LIGO events: binary black holes mergings

V. M. Lipunov, K. A. Postnov and M. E. Prokhorov

Moscow State University, Sternberg Astronomical Institute, 119899 Moscow, Russia
e-mail: lipunov@sai.msu.su; pk@sai.msu.su; mike@sai.msu.su
fax: +7 (095) 932 88 41

Abstract

Based on evolutionary scenarios for binary stellar evolution we study the merging rates of relativistic binary stars (NS+NS, NS+BH, BH+BH) under different assumptions of BH formation. We find the BH+BH merging rate in the range one per 200,000 – 500,000 year in a Milky-Way type galaxy, while the NS+NS merging rate R_{ns} is approximately 10 times as high, which means that the expected event rate even for high mean kick velocities of NS up to 400 km/s is at least 30-50 binary NS mergings per year from within a distance of 200 Mpc.

As typical BH is formed with a mass 3-10 times the NS mass (assumed 1.4 $M_\odot$), the rates obtained imply that the expected detection rate of binary BH by a LIGO-type gravitational wave detector is 10-100 times higher than the binary NS merging rate for a wide range of parameters.

Key words: 95.85.Sz; 97.60.Lf; gravitational waves – stars: evolution – stars: neutron – stars: black holes

1 Introduction

The final merging stages of binary relativistic star evolution containing two compact starts (NS or BH) that merge on a time-scale shorter than the Hubble time are among the primary targets for gravitational wave interferometers currently under construction (LIGO, VIRGO, GEO-600) (Abramovici et al. 1992; Schutz 1996).

It is very important to know the accurate rate of such events, as the planned LIGO sensitivity will allow detection of NS+NS mergings out to ~ 200 Mpc. The galactic merging rate of binary NS have constantly been made over last 20

years and still presents a large controversy spanning from one per several 1000 yr to several 100000 yr. The "optimistic" high merging rate have been persistently obtained from theoretical considerations (Clark et al. 1979, Lipunov et al. 1987, Narayan et al. 1991, Tutukov & Yungelson 1993, Lipunov et al. 1995, Dalton & Sarazin 1995, Portegies Zwart & Spreeuw (1996)), whereas the "ultraconservative" and "realistic" estimates rely upon binary pulsar statistics only (Phinney 1991, Curran & Lorimer 1995, van den Heuvel & Lorimer 1996) involving as minimum as possible (if any) theoretical arguments.

A criticism of the theoretical evolutionary estimates is usually made with the reference to a large number of poorly determined parameters of the evolutionary scenario for massive binary systems, such as common envelope stage efficiency, initial mass ratio distribution, distribution of the recoil velocity imparted to NS at birth etc. (Lipunov et al. 1996a). However, by comparing the results of the Scenario Machine calculations with other observations (Lipunov et al. 1996a) we may fix some free parameters (such as the form of the initial mass ratio distribution and the common envelope efficiency), and then examine the dependence of the double NS merging rate on one free parameter, say the mean kick velocity value. In fact, the calculations turn out to be most sensitive to just the kick velocity (Lipunov et al. 1996b) as the binary system gets more chances to be disrupted during supernova explosion, especially when the recoil velocity becomes higher than the orbital velocity of stars in the system. This becomes especially important in view of new pulsar velocity determination (Lyne & Lorimer 1994) which is indicative of a very high mean space velocity of $\sim 400 - 500$ km/s.

The situation is even more poor with binaries containing BH – no BH+NS system is known so far (despite a not too pessimistic theoretical prediction of 1 PSR+BH per 1000 single radiopulsars; Lipunov et al. 1994), hence no "conservative" estimates can be done. Theoretically, however, putting aside the absolute galactic value of NS+NS and NS/BH+BH merging rates, we may estimate the ratio of the both, $N = R_{bh}/R_{ns}$. The important main parameters here are the threshold mass of a star evolving to a black hole, M_{cr}, the mass of the BH formed during the collapse, M_{bh}, and the kick velocity the BH acquires.

In this paper we calculate this ratio within the framework of different evolutionary scenarios for massive binary star evolution for a wide range of parameters. We find that typically galactic binary BH merging rate R_{bh} is 1-2 orders of magnitude less than R_{ns}, with a smaller difference for high kick velocities imparted to NS at birth. Nonetheless, since the typical BH mass is 3-10 times higher than that of NS and gravitational waveform's dimensionless amplitude h_c from a coalescing binary nearly linearly depends upon mass involved, a GW-detector with a given noise level will be sensitive to 3-10 times farther BH-systems. Therefore one may expect a comparable and even higher number of BH-events than NS-events over the same observational time, which is of

important fundamental character.

Qualitatively, a crude estimate of the ratio of BH-containing binary merging rate to NS binary merging rate may be done as follows. Let us assume the mass of BH progenitor to be $35M_\odot$, which would correspond roughly to $M_{ms} \sim 60M_\odot$ on the main sequence (since according to the evolutionary scenario, the mass of a star after mass transfer is $M_{core} \simeq 0.1M_{ms}^{1.4}$). On the other hand, any star with $M_{ms} \geq 10M_\odot$ evolves to form a NS. Using the Salpeter mass function ($f(M) \propto M^{-2.35}$), we obtain that BH formation rate relates to NS formation rate as $(60/10)^{-1.35} \approx 0.09$. Extrapolating this logic to binary BH/NS systems, we might expect $R_{bh}/R_{ns} \sim 1/10$, to a half-order accuracy. Actually, the situation is complicated by several factors: the presence of the kick velocity during supernova explosion which may act more efficiently in the case of NS formation; mass exchange between the components; distribution by mass ratio, etc. All these factors will be accounted for in our calculations.

To perform evolutionary calculations, we apply the Monte-Carlo method for binary stellar evolution studies developed by us over last ten years; we refer to Lipunov et al. 1996a,b,c for a detailed description of the method and evolutionary scenarios used.

2 Parameters of black hole formation

A black hole is known to be fully described by three parameters: its mass M_{bh}, angular momentum, and electric charge. For our purposes, however, only mass is important as it determines the orbital evolution when the BH enters a close binary system. Since no exact theory of stellar-mass BH formation exists, we should somehow parametrize it. Here we may either fix the initial mass of main-sequence star, M_{ms}, that yields a BH in the end of its evolution, or fix the threshold pre-supernova mass, M_*, that collapses into a BH. The second parameter is the mass of BH itself, which we assume to be linearly proportional to the pre-supernova mass: $M_{bh} = k_{bh}M_*$, $0 < k_{bh} \leq 1$. In the case of single stars these two means are fully equivalent, while when in a close binary with mass exchange between the components they may be thought to give different results. Physically, the latter parametrization (M_*, k_{bh}) seems more preferable. In fact, we tried both variants and found them giving only slightly different figures.

Among other parameters of BH formation in binaries, the kick velocity imparted to BH during the collapse is the most crucial from the point of view of binary system evolution. We assume a universal mechanism giving anisotropic velocity for both neutron stars and black holes, with BH kick velocity w_{bh} be-

ing proportional to the mass lost during the collapse:

$$w_{bh} = w_{ns} \frac{1 - k_{bh}}{1 - \frac{M_{OV}}{M_*}} \quad (1)$$

where $M_{OV} = 2.5\mathrm{M}_\odot$ is the Oppenheimer-Volkoff limit for NS mass. This law is chosen assuming boundary conditions $w_{bh} = 0$ at $k_{bh} = 1$ (i.e. when the total mass of the collapsing star goes into a BH) and $w_{bh} = w_{ns}$ once $M_{bh} = M_{OV}$.

The 3-D kick velocity is assumed to be arbitrarily oriented in space and to be distributed so as to fit Lyne-Lorimer pulsars' transverse velocities (Lyne & Lorimer, 1994) (see Lipunov et al. 1996ab):

$$f_{LL}(x) \propto \frac{x^{0.19}}{(1 + x^{6.72})^{1/2}} \quad (2)$$

where $x = w/w_0$, w_0 is a parameter, it fits well the Lyne & Lorimer's 2D-distribution at $w_0 = 400$ km/s.

3 The detection rate of BH mergings versus NS mergings

Fig. 1 shows the relativistic compact binaries' merging rates as a function of the mean kick velocity assuming Lyne-Lorimer kick velocity distribution (2). In this variant, BH parameters were chosen $M_* = 35M_\odot, k_{bh} = 0.3$, i.e. BH with masses $M_{bh} > 11.5M_\odot$ were formed during evolution. From Fig. 1 we see that the theoretical expectation for the NS+NS merging rate in a model spiral galaxy with a typical mass of 10^{11} $\mathrm{M}_\odot$ lie within the range from $\sim 3 \times 10^{-4}$ yr^{-1} to $\sim 10^{-5}$ yr^{-1}, depending on the assumed mean kick velocity and the shape of its distribution. For Lyne & Lorimer kick velocity law with the mean value of 400 km/s, we obtain $R_{NS+NS} \approx 5 \times 10^{-5}$ yr^{-1}. To obtain the merging rate from a given volume V in the Universe, the galactic rate should be scaled, for example, using Phinney's formula (Phinney 1991): $\mathcal{R} \approx 0.01 h_{100} R \times V$.

Two details from Fig. 1 are worth noting: 1) the binding effect at small kick velocities and 2) the smaller effect of high kicks on the BH+BH rate. The first fact is qualitatively clear: a high kick leads to the system disruption; however, if the system is survived the explosion, its orbit would have a periastron always smaller than in the case without kick. During the subsequent tidal circularization a closer binary system will form which will spend less time prior to the merging. The binding effect of small recoil velocities is very pronounced in the case of binary BH. At higher kicks their merging rate decreases slower due to higher masses of the components.

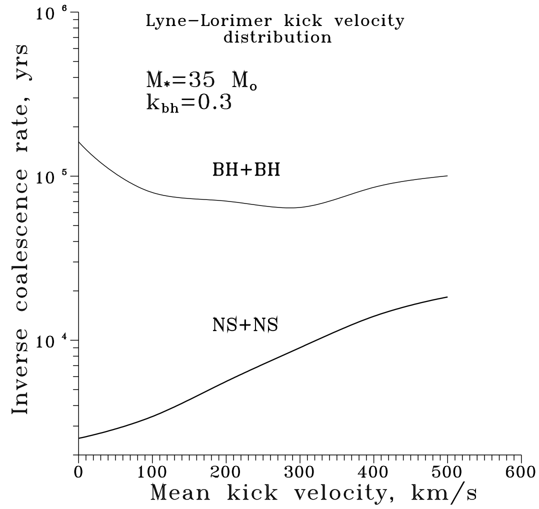

Fig. 1. The galactic merging rate of NS+NS and BH+BH binaries for Lyne-Lorimer kick velocity distribution as a function of the mean kick velocity assuming BH formation parameters $M_* = 35M_\odot, k_{bh} = 0.3$

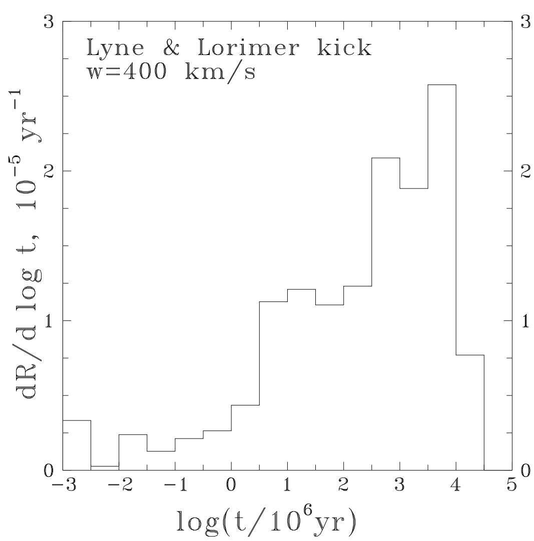

Fig. 2. The galactic birthrate of merging NS with different ages (the time from NS formation to merging) for Lyne-Lorimer kick velocity distribution and $w = 400$ km/s.

We also present the distribution of merging neutron stars by their ages (the time from the birth to merging) for "standard" scenario parameters (see the Appendix) and Lyne-Lorimer kick velocity distribution with $w = 400$ km/s. Clearly, the characteristic ages of merging neutron stars range from 10^8 to 10^{10} years and the vast majority of all merging neutron stars are much older than charatceristic pulsar age of 5×10^6 years. This is important for understanding the difference between evolutionary and pulsar-statistics-based estimates of NS+NS merging rates (see the Discussion).

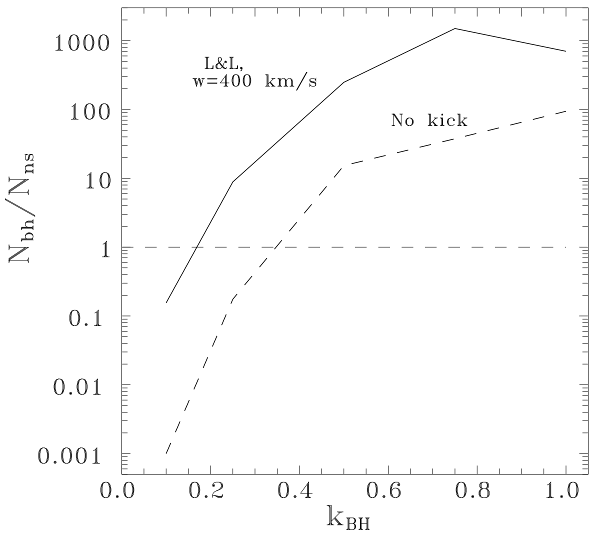

Fig. 3. The ratio of BH+BH to NS+NS merging events as expected to be detected by a gravitational wave detector with a given sensitivity, as a function of parameter k_{bh} (with $M_* = 35M_\odot$) assuming Lyne-Lorimer kick velocity distribution with $w_0 = 400$ km/s (solid curve) and without kick (dashed curve)

Since the characteristic dimensionless strain metric amplitude from a merging binary system, h_c, scales as $M^{5/6}/r$, where M is a characteristic mass of binary companions and r is a distance to the source (Abramovici al. 1992)), the number of events registered by the detector scales as

$$\frac{N_{bh}}{N_{ns}} \approx \left(\frac{R_{bh}}{R_{ns}}\right)\left(\frac{M_{bh}}{M_{ns}}\right)^{15/6}$$

Clearly, the second factor in this expression may overcome the first one (which is of order 0.1-0.01) if typical BH masses is several times as high as the NS mass.

Fig. 3 demonstrates the relative detection rate of coalescing BH and NS binaries obtained by a gravitational wave detector with given sensitivity. Lyne-Lorimer kick velocity distribution with $w_0 = 400$ km/s were assumed. Here we fixed $M_* = 35M_\odot$ and varied k_{bh}. Other scenario parameters (such as the form of the initial mass ratio distribution and common envelope efficiency) only slightly affect the results. It is seen that the ratio of the expected detection rates for merging BH/NS binaries (3) may well exceed unity for a wide range of parameters.

4 Discussion and conclusions

The NS+NS merging rates obtained by us is an order of magnitude higher than those obtained by Portegies Zwart and Spreeuw (1996). Whereas we both use the same mean kick velocity $w = 400$ km/s, the shapes of kick velocity distribution are totally different: Portegies Zwart and Spreeuw (1996) use a Maxwellian distribution which produces a strong deficit of slow pulsars relative to the observed distribution (Lyne & Lorimer 1994). In our other paper (see Lipunov et al. 1996b) we also perform calculations for the Maxwellian kick velocity distributions and find full agreement with calculations of Portegies Zwart and Spreeuw. We also showed (Lipunov et al 1996a, Fig. 9-10) that the Maxwellian distribution with $w = 400$ km/s does not describe the observed pulsar velocity distribution at low velocities and, moreover, strongly contradict to the binary pulsar statistics in general.

Our galactic NS+NS merging rate (5×10^{-5} yr^{-1}) is also exceeds the so-called "Bailes upper limit" to the NS+NS birthrate in the Galaxy $\sim 10^{-5}$ yr^{-1} (Bailes, 1996). Indeed, following Bailes, the fraction of "normal" pulsars in NS+NS binaries which potentially could merge during the Hubble time among the total number of known pulsars is less than $\sim 1/700$. Multiplying this by the birthrate of "normal" pulsars $1/125$ yr-1 we get this limit 10^{-5} yr^{-1}. Our value is 5 times higher for Lyne-Lorimer kick velocity distribution at $w = 400$ km/s. First we note that the accuracy of Bailes limit is a half-order at best; in addition, the pulsar birthrate $1/125$ yr^{-1} is at least 5 times lower than the birthrate of massive stars ($> 10M_{\odot}$) in our Galaxy according to Salpeter mass function (once per 25 years) which produce neutron stars in the framework of the modern evolutionary scenario. This discrepancy may be decreased if we take into account the uncertainty in the pulsar beaming factor and, which may be more important, the still-present uncertainty in pulsar distance scale which influences the estimate of the total galactic number of pulsars and hence their birthrate.

On the other hand, the "best guess" observational limit for NS+NS merging rate (Phinney 1991; van den Heuvel and Lorimer 1996) yields $\sim 8 \times 10^{-6}$ yr^{-1} which is an order of magnitude smaller than our calculated rate. Possible explanations to this discrepancy could be that many binary NS are born in close orbits and merge in a short time, as was suggested by van den Heuvel (1992) (see also Tutukov & Yungelson (1993); note, however, that our calculations and Fig. 1 of Tutukov and Yungelson's paper show that binary NS+NS with time before coalescence less than 10^7 years contributes only $\sim 10-20\%$ to the total galactic merging rate). We specially calculated the distribution of merging neutron stars by their ages (see Fig. 2). It is seen that the mean age of merging NS is about 10^8 years; the fraction of merging NS with ages shorter than 5×10^6 years is 15%; so the observational underestimation is mainly

due to a large portion of relativistic binaries containing no pulsar (ejecting neutron star) and thus being unobservable by traditional radioastronomical means (Lipunov et al. 1996b).

The example calculations presented above clearly show that the expected detection rate of mergings with BH may turn out to be much higher than those with NS. In view of the great fundamental importance of this finding, the question arises how stable is this result against changing of other (numerous) parameters? The parameters used in evolutionary calculations may be subdivided into several groups:

(1) parameters of BH formation (such as progenitor's mass, BH mass, kick velocity during the collapse);

(2) parameters of binary evolutionary scenario (such as initial mass ratio distribution, mass transfer treatment, common envelope efficiency, kick velocity distribution shape, etc.);

(3) general parameters of stellar evolution (mass loss rate at different stage, convection treatment, etc.).

In the present paper we focused on BH formation parameters fixing others on the grounds discussing elsewhere (see Lipunov et al. 1996a). In a separate paper (Lipunov et al. 1996b) we study the influence of the most important of them (the common envelope efficiency, the initial mass ratio distribution, the shape of the kick velocity distribution, mass loss by single stars), and come to essentially the same conclusion: the expected number of binary BH mergings exceeds that of NS merging for a wide range of parameters!

This urges studies on possibly exact calculation of GW-waveforms emitted during BH coalescences to obtain maximum information on this fundamental and probably the most spectacular natural phenomenon.

Acknowledgements

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5 Appendix: The evolutionary scenario model

Monte-Carlo simulations of binary evolution allows one to study the evolution of a large ensemble of binaries and to estimate the number of binaries at different evolutionary stages. This method has become popular over last ten years (Kornilov & Lipunov 1984; Dewey & Cordes 1987; Bailes 1989; for another applications of Monte-Carlo simulations see de Kool 1992; Tutukov & Yungelson 1993; Pols & Marinus 1994).

For modeling binary evolution, we use the "Scenario Machine", a computer code that includes a modern scenario of binary evolution (for a review, see van den Heuvel (1994)) and takes into account the influence of magnetic field of compact objects on their observational appearance. A detailed description of the computational techniques and input assumptions is summarized elsewhere (Lipunov et al. 1996a), and here we list only basic parameters and initial distributions.

5.1 Initial binary parameters

The initial parameters determining binary evolution are: the mass of the primary ZAMS component, M_1; the binary mass ratio, $q = M_2/M_1 < 1$; the orbital separation, a. We assume zero initial eccentricity.

The distribution of initial binaries over orbital separations is known from observations (Abt 1983):

$$\begin{aligned} &f(\log a) = \mathrm{const}\,, \\ &\max\ \{10\ \mathrm{R}_\odot,\ \mathrm{Roche\ Lobe}\ (M_1)\} < \log a < 10^4\ \mathrm{R}_\odot. \end{aligned} \tag{3}$$

The initial mass ratio distribution in binaries, being very crucial for overall evolution of a particular binary system (Trimble 1983), has not yet been derived somehow reliably from observations due to a number of selection effects. A 'zero assumption' usually made is that the mass ratio distribution has a flat shape, i.e. the high mass ratio binaries are formed as frequently as those with equal masses (e.g. van den Heuvel 1994). Ignoring the real distribution, we parametrized it by a power law, assuming the primary mass distribution to obey the Salpeter mass function (Salpeter 1955):

$$\begin{aligned} &f(M_1) \propto M_1^{-2.35}\,, \quad 10\ \mathrm{M}_\odot < M_1 < 120\ \mathrm{M}_\odot\,; \\ &f(q) \propto q^{\alpha_q}\,, \qquad\quad q \equiv M_2/M_1 < 1\,; \end{aligned} \tag{4}$$

A comparison of the observed X-ray source statistics with the predictions of

the current evolutionary scenarios indicates (Lipunov et al. 1996a) that the initial mass ratio should be strongly centered around unity, ($\alpha_q \sim 2$). Of course, this is not a unique way of approximating the initial binary mass ratio (see e.g. Tout (1991)). However, from the point of view of binary NS merging rate, this parameter affects the results much less than the kick velocity. In the present paper, we use both $\alpha_q = 2$ and $\alpha_q = 0$.

5.2 Initial parameters of compact stars

We are interested in binary NS or NS+BH systems, so it is enough to trace evolution of binaries with primary masses $M_1 > 10M_\odot$ which are capable of producing NS and BH in the end of evolution. The secondary component can have a mass from the whole range of stellar masses $0.1M_\odot < M_2 < 120M_\odot$.

We consider a NS with a mass of 1.4 $M_\odot$ to be a result of the collapse of a star with the core mass prior to the collapse $M_* \sim (2.5-35)$ $M_\odot$. This corresponds to an initial mass range $\sim (10-60)$ $M_\odot$, considering that a massive star can loose more than $\sim (10-20)\%$ of its initial mass during the evolution with a strong stellar wind (de Jager 1980).

The magnetic field of a rotating NS largely defines the evolutionary stage the star would have in a binary system (Schwartzman 1970; Davidson & Ostriker 1973; Illarionov & Sunyaev 1975). We use a general classification scheme for magnetized objects elaborated by Lipunov (1992).

Briefly, the evolutionary stage of a rotating magnetized NS in a binary system depends on the star's spin period P (or spin frequency $\omega = 2\pi/P$), its magnetic field strength B (or, equivalently, magnetic dipole moment $\mu = BR^3/2$, where R is the NS radius), and the physical parameters of the surrounding plasma (such as density ρ and sound velocity v_s) supplied by the secondary star. The latter, in turn, could be a normal optical main sequence (MS) star, or red giant, or another compact star). In terms of the Lipunov's formalism, the NS evolutionary stage is determined by one or another inequality between the following characteristic radii: the light cylinder radius of the NS, $R_l = c/\omega$ (c is the speed of light); the corotation radius, $R_c = (GM/\omega^2)^{1/3}$; the gravitational capture radius, $R_G = 2GM/v^2$ (where G is the Newtonian gravitational constant and v is the NS velocity relative to the surrounding plasma); and the stopping radius R_{stop}. The latter is a characteristic distance at which the ram pressure of the accreting matter matches either the NS magnetosphere pressure (this radius is called Alfven radius, R_A) or the pressure of relativistic particles ejected by the rotating magnetized NS (this radius is called Schwartzman radius, R_{Sh}). For instance, if $R_l > R_G$ then the NS is in the ejector stage (E-stage) and can be observed as a radiopulsar; if $R_c < R_A < R_G$, then so-called

propeller regime is established (Illarionov & Sunyaev 1975) and the matter is expelled by the rotating magnetosphere; if $R_A < R_c < R_G$, we deal with an accreting NS (A-stage), etc. These inequalities can easily be translated into relationships between the spin period P and some critical period that depends on μ, the orbital parameters, and accretion rate $\dot{M}$ (the latter relates v, v_s, ρ, and the binary's major semiaxis a via the continuity equation). Thus, the evolution of a NS in a binary system is essentially reduced to the NS spin evolution $\omega(t)$, which, in turn, is determined by the evolution of the secondary component and orbital separation $a(t)$. Typically, a single NS embedded into the interstellar medium evolves as $E \to P \to A$ (for details, see Lipunov & Popov 1995). For a NS in a binary, the evolution complicates as the secondary star evolves: for example, $E \to P \to A \to E$ (recycling), etc.

When the secondary component in a binary overfills its Roche lobe, the rate of accretion onto the compact star can reach the value corresponding to the Eddington luminosity $L_{Edd} \simeq 10^{38}$ $(M/\mathrm{M}_{\odot})$ erg/s at the R_{stop}; then a supercritical regime sets in (not only superaccretors but superpropellers and superejectors can exist as well; see Lipunov 1992).

If a BH is formed in due course of the evolution, it can only appear as an accreting or superaccreting X-ray source; other very interesting stages such as BH + radiopulsar which may constitute a notable fraction of all binary pulsars after a starburst are considered in Lipunov et al. (1994).

The initial distribution of magnetic fields of NS is another important parameter of the model. This cannot be taken from studying pulsar magnetic field (clearly, pulsars with highest and lowest fields are difficult to observe). In the present calculations we assume a flat distribution for dipole magnetic moments of newborn NS

$$f(\log\mu) = \text{ const}\,, \quad 10^{28} \leq \mu \leq 10^{32}\ \mathrm{G\ cm}^3\,, \tag{5}$$

and the initial rotational period of the NS is assumed to be 1 ms.

The computations were made under different assumptions about the NS magnetic field decay, taken in an exponential form, $\mu(t) \propto \exp(-t/tau)$, where τ is the characteristic decay time of $10^7 - 10^8$ year. The field is assumed to stop decaying below a minimum value of 10^9 G (van den Heuvel et al. 1986). No accretion-induced magnetic field decay is assumed.

A radiopulsar was assumed to be turned "on" until its period P has reached a "death-line" value defined from the relation $\mu_{30}/P^2_{death} = 0.4$, where μ_{30} is the dipole magnetic moment in units of 10^{30} G cm^3, and P is taken in seconds.

The mass limit for NS (the Oppenheimer-Volkoff limit) is $M_{OV} = 2.5\ \mathrm{M}_{\odot}$,

which corresponds to a hard equation of state of the NS matter. The most massive stars are assumed to collapse into a BH once their mass before the collapse is $M > M_{cr} = 35$ M$_\odot$ (which would correspond to an initial mass of the ZAMS star ~ 60 M$_\odot$ since a substantial mass loss due to a strong stellar wind occurs for the most massive stars). The BH mass is calculated as $M_{bh} = k_{bh} M_{cr}$, where the parameter k_{bh} is taken to be 0.3, as follows from the studies of binary NS+BH (Lipunov et al. 1994).

5.3 *Other parameters of the evolutionary scenario*

The fate of a binary star during evolution mainly depends on the initial masses of the components and their orbital separation. The mass loss and kick velocity are the processes leading to the binary system disruption; however, there are a number of processes connected with the orbital momentum losses tending to bound the binary (e.g., gravitational radiation, magnetic stellar wind).

5.3.1 *Common envelope stage*

We consider stars with a constant (solar) chemical composition. The process of mass transfer between the binary components is treated according to the prescription given in van den Heuvel (1994) (see Lipunov et al. (1996a) for more detail). The non-conservativeness of the mass transfer is treated via "isotropic re-emission" mode (Bhattacharya & van den Heuvel 1991). If the rate of accretion from one star to another is sufficiently high (e.g. the mass transfer occurs on a timescale 10 times shorter than the thermal Kelvin-Helmholz time for the normal companion), or the compact object is engulfed by a giant companion, the common envelope (CE) stage of the binary evolution can set in (see Paczyński 1976; van den Heuvel 1983).

During the CE stage, an effective spiral-in of the binary components occurs. This complicated process is not fully understood as yet, so we use the conventional energy consideration to find the binary system characteristics after the CE stage by introducing a parameter α_{CE} that measures what fraction of the system's orbital energy goes, between the beginning and the end of the spiralling-in process, into the binding energy (gravitational minus thermal) of the ejected common envelope. Thus,

$$\alpha_{CE}\left(\frac{GM_aM_c}{2a_f} - \frac{GM_aM_d}{2a_i}\right) = \frac{GM_d\left(M_d - M_c\right)}{R_d}\,, \qquad (6)$$

where M_c is the mass of the core of the mass loosing star of initial mass M_d and radius R_d (which is simply a function of the initial separation a_i and the

initial mass ratio M_a/M_d), and no substantial mass growth for the accretor is assumed (see, however, Chevalier 1993). The less α_{CE}, the closer becomes binary after the CE stage. This parameter is poorly known and we varied it from 0.5 to 10 during calculations.

5.3.2 High and low mass-loss scenario form massive star evolution

A very important parameter of the evolutionary scenario is the stellar wind mass loss effective for massive stars. No consensus on how stellar wind mass loss occurs in massive stars exist. So in the spirit of our scenario approach we use two "extreme", in a sense, cases. The "low mass-loss" scenario treats the stellar wind from a massive star of luminosity L according to de Jager's prescription

$$\dot{M} \propto \frac{L}{cv_\infty}$$

where c and v_∞ are the speed of light and of the stellar wind at infinity, respectively. This leads to at most 30 per cent mass loss for most massive stars.

The "high stellar wind mass-loss" scenario uses calculations of single star evolution by Schaller et al. (1992). According to these calculations, a massive star lose most of its mass by stellar wind down to 8-10 $M_\odot$ before the collapse, practically independently on its initial mass. In this case we assume the same mechanism for BH formation as for the "low mass-loss" scenario, but only one parameter k_{bh} remains (M_{cr} is taken from evolutionary tracks). Masses of BH formed within the framework of the high mass-loss scenario are thus always less than or about of 8 $M_\odot$.

So far we are unable to choose between the two scenarios; however, recently reported observations of a very massive WR star of 72 $M_\odot$ (Rauw et al. 1996) cast some doubts on very high mass-loss scenario or may imply that different mechanisms drive stellar wind mass loss.

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